

## **Coupled Ocean-Atmosphere Modeling of the Coastal Zone**

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### **LONG-TERM GOAL**

The long-range goal of this project is to improve our ability to understand and predict environmental conditions in the coastal zone.

### **OBJECTIVES**

The primary scientific objectives of the proposed research are to use a coupled atmosphere--ocean model to investigate and quantify the interaction between the oceanic and atmospheric boundary layers and its effect on environmental conditions in the coastal zone. The main focus will be on boundary layer interactions under coastal upwelling conditions, in which cold, upwelled ocean surface water induces the development of stable internal boundary layers in the atmosphere and thereby reduces low-level winds and surface stress. Research will also investigate the effects of coastal terrain and diurnal heating and the interaction of forced coastal atmospheric flows on the ocean circulation.

### **APPROACH**

The approach used in this project is to combine numerical model results with in-situ and remote-sensing observations to understand and quantify physical processes in the coastal, coupled atmosphere-ocean and test their representation in mesoscale atmospheric models.

### **WORK COMPLETED**

Efforts this year have focused on understanding the relative importance of atmosphere-ocean coupling in comparison with coastal terrain and diurnal forcing. Simulations were conducted using an idealized coastline with a single point, and emphasized how coastal features interact with diurnal heating and boundary layer coupling. Results with and without coupling are presented in this report and analyzed with respect to previous observations of the coupled response of the ocean/atmosphere. Results from cloud resolving LES experiments are also presented for cases with fog and stratus.

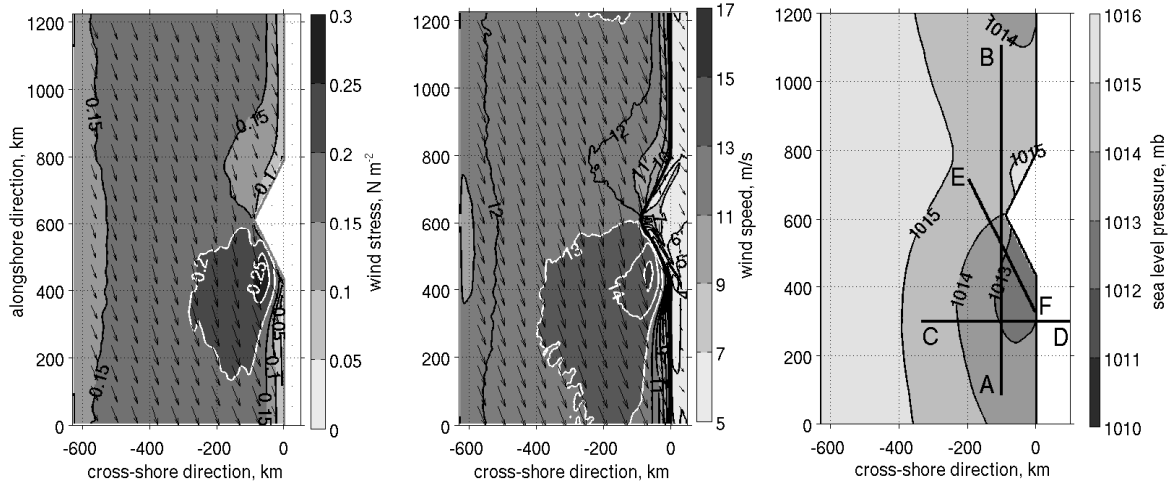
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## RESULTS

### Coupled Circulation

Simulations with the coupled Naval Research Laboratory (NRL) COAMPS and Regional Ocean Modeling System (ROMS) were conducted for an idealized coastal terrain consisting of a single cape with a periodic north-south boundary. Forcing conditions representing typical northerly winds during the summer months were applied over a 14-day period with diurnal heating. Simulations with coupling and constant SST were performed and are analyzed below.

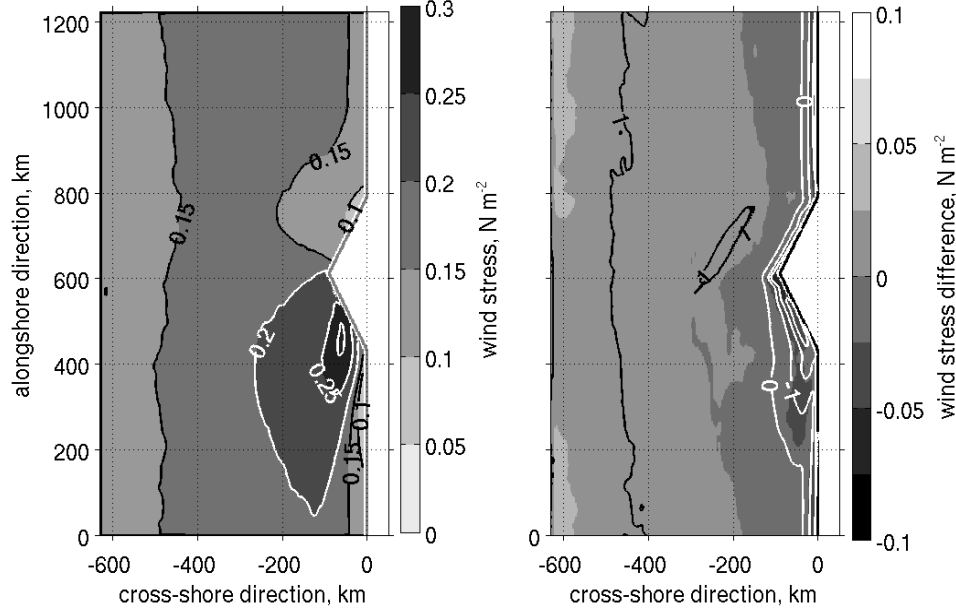
In the coupled case, upwelling generates reduced wind stress over the colder water adjacent to the coast. Nearshore winds are also affected by the coastal terrain subject and diurnal forcing, which may result in substantial wind stress gradients as well. To separate these effects from that of the upwelling, we conducted a second experiment by simulating a case with SST held invariant in time and space and at a fixed initial value ( $14^{\circ}\text{C}$ ), thus eliminating ocean feedback to the atmosphere. Since the differences in wind stress fields in these two cases can result only from the evolution of the SST in the coupled case, comparison of the cases provides a convenient framework for analyzing the wind stress—SST interaction.



**Figure 1. (a) Mean wind stress components and magnitude ( $\text{N m}^{-2}$ ) from the coupled simulation, averaged for 10 days (forecast hours 37-276); (b) mean 10-m wind components and speed (m/s) for the same period; (c) mean sea level pressure (mb) for the same period. Hourly means of the wind stress components were computed using the values at each time step of the atmospheric model. Wind stress magnitude was computed for each hour from the corresponding hourly means of its components, and then averaged over 10 days. The average 10-m wind speed was computed from hourly model output of the instantaneous values of wind components. Vectors are plotted every  $20^{\text{th}}$  point of the model grid to avoid clutter. Black lines in c) are indicate cross-section locations presented in subsequent figures.**

Average wind stress magnitudes in the coupled control case and fixed-SST case are shown in Fig. 1 and Fig.2(a), along with average differences of hourly wind stresses and SSTs between the control case and fixed-SST case in Fig. 2(b). The wind stress field in the fixed-SST case is qualitatively similar to that of the control case, featuring an area of stronger wind stresses in the lee side of the cape. Higher

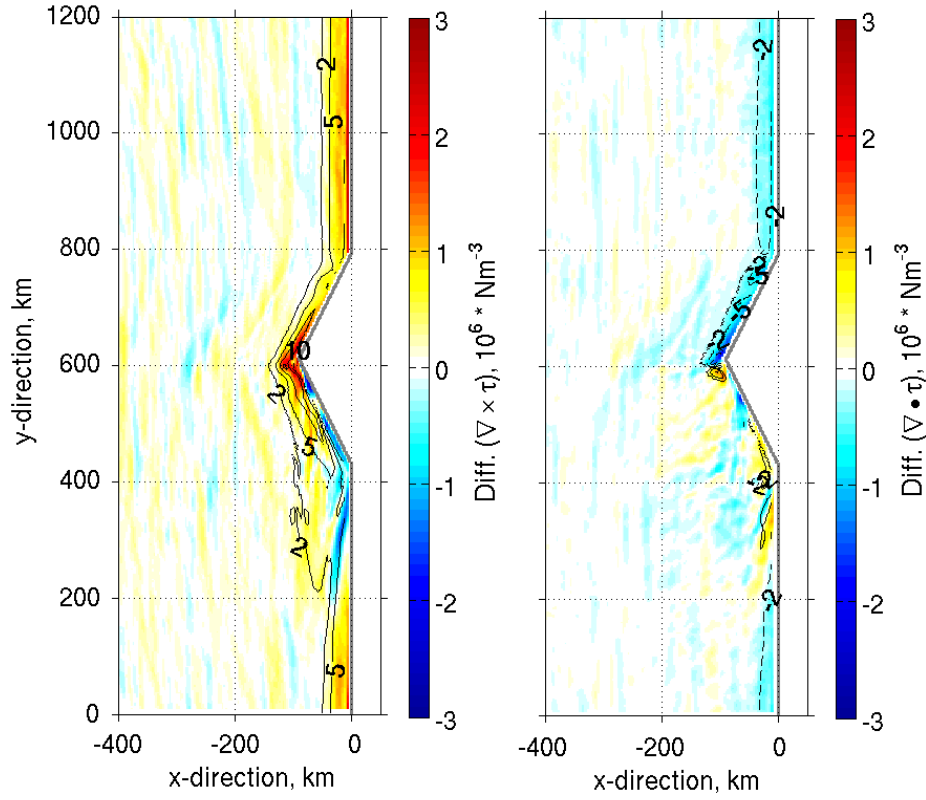
wind stresses, however, are found within 100-200 km along the entire coastline in the fixed-SST case, as is also indicated by the difference field, and the highest differences occur in the downwind region. Average wind stress magnitude differences between the two cases correspond well with the SST differences: negative values are commonly found in both quantities inshore of the upwelling front (within ~50-100 km of the coast), and positive values are beyond ~200 km off the coast. Area of negative SST differences in the lee side of the cape corresponds to the wider upwelling region in the coupled case. An area of positive SST differences results about 150 km offshore along the windward side of the cape, which is the upstream edge of the change in ocean bottom topography, for the open ocean – continental shelf break transition. It is likely that the southward oceanic flow adjustment on the upstream side of this bathymetric feature affects the SST-s in the coupled case.



**Figure 2. (a) Wind stress ( $N m^{-2}$ ) from the fixed-SST simulation, averaged for 10 days; (b) average differences in wind stresses (shading,  $N m^{-2}$ ) and average differences in SST (contours,  $^{\circ}C$ ) between the coupled and fixed-SST cases. Contour intervals for SST differences are  $1^{\circ}C$ , and are black for positive values, white for 0 and negative values.**

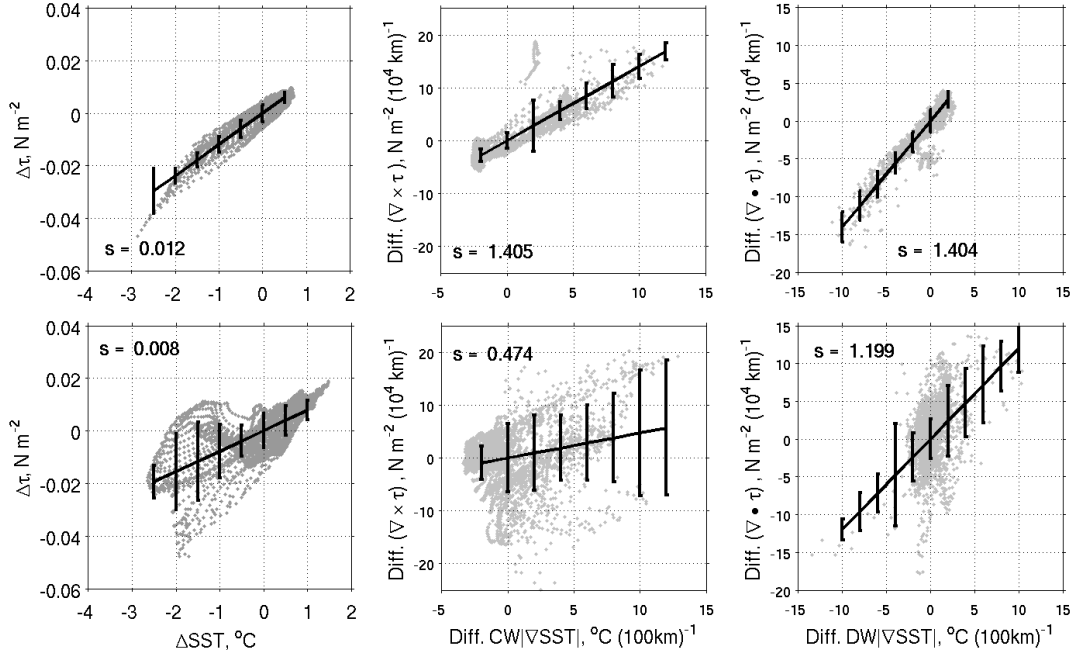
Study of wind stress – SST coupling from their derivatives could be done similarly to the coupled case, except using the average differences data. The average differences in wind stress curl and wind stress divergence between the coupled and partially coupled cases are shown in Fig. 3; the overlaid contours are the “differences” in CWSST and DWSST between the same cases. Note that due to the fixed-SST case being spatially uniform, both CWSST and DWSST are zero. Thus, the differences in CWSST and DWSST in Fig. 3 are solely determined by their corresponding values from the coupled case. Higher wind stress curl (convergence) results in the coupled case within the 50 km of the coast in the upwind region, as evidenced by positive (negative), and the correspondence with SST derivative fields is also high in that area for both pairs. Visual correspondence of the differences in the downwind region of the wind stress curl – CWSST and wind stress divergence – DWSST pairs is worse than in the upwind region, but shows considerable improvement compared to those from the coupled case.

Scatterplots and linear fits for the three pairs of differences are shown in Fig.4, separately for the two regions (inshore 100 km). A consistent response of wind stress to SST changes is seen for the upwind



**Figure 3.** Ten-day average differences between the coupled and fixed-SST simulations in a) wind stress curl (colors,  $10^6 \cdot \text{N m}^{-3}$ ) and cross-wind SST gradients (contours,  $^{\circ}\text{C (100 km)}^{-1}$ ), b) wind stress divergence (colors,  $10^6 \cdot \text{N m}^{-3}$ ) and downwind SST gradient (contours,  $^{\circ}\text{C (100 km)}^{-1}$ ).

region, resulting in increase of about  $0.12 \text{ Nm}^{-2}$  in wind stress per  $10^{\circ}\text{C}$  of temperature change. This response is weaker,  $0.08 \text{ N m}^{-2}$  per  $10^{\circ}\text{C}$  for the downwind region and is characterized by higher scatter. The wind stress curl – CWSST difference plot yields coefficients of 1.41 and 0.47 for the upwind and downwind regions, respectively, and high scatter of the values in the downwind region. The coefficients for wind stress divergence–DWSST differences are closer for the two regions, 1.40 and 1.20 for the upwind and downwind region, correspondingly. High scatter in the downwind region, however, in some way reduces the significance of the resulting higher value. Thus, as follows from the analysis of the time-average differences between the coupled and fixed-SST cases, wind stress – SST correlations are weaker on the lee side of the cape, than on the windward side.



**Figure 4.** Scatterplot and linear fit for the time-average differences between the coupled simulation and fixed-SST simulation, of the following quantities: (a) wind stress vs. SST, (b) wind stress curl vs. CWSST, and (c) wind stress divergence vs. DWSST gradient. Top panels: points in the “upwind region”; bottom panels: points in the “downwind region”. All calculations are limited to the points within 100 km off the coast.

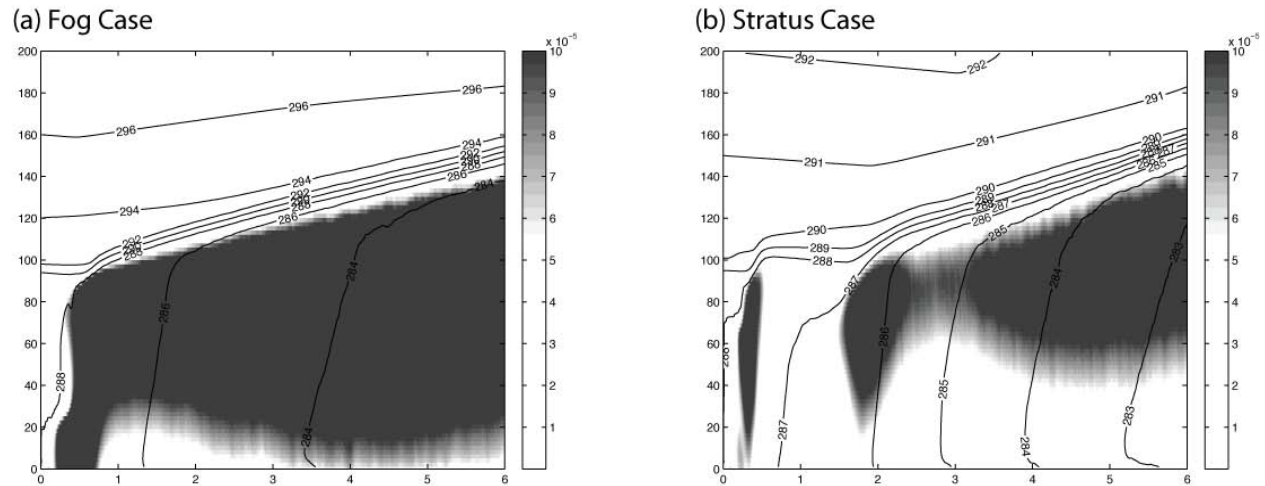
## Fog Simulations

Low clouds and fog are often observed in the marine environment and are notoriously difficult to predict with reasonable accuracy. Poor predictability is partly explained by the sensitivity of fog to slight changes in the sea-surface temperature (SST) and vertical stability of the atmosphere. For example, it is not uncommon along the U.S. west coast for fog to form as the marine boundary layer moves over water with just slightly warmer (1 °C) SST. Work performed here aims to better define the conditions that lead to fog and low cloud formation, and provide some understanding of the processes that govern fog evolution.

Typical conditions favoring fog in the coastal environment are strong subsidence over a cold water surface. Soundings during fog events frequently have a very shallow boundary layer capped by a strong increase in potential temperature and a rapid decrease in the dew point temperature. This juxtaposition of very dry, warm air over cold, saturated air would seem to favor erosion of the low level fog, however, mixing is typically very weak at the inversion so that fluxes of heat and moisture are unable to offset surface fluxes and radiative cooling from the fog top. In fact, simulations using a large-eddy simulation (LES) cloud model show that the inversion must be strong at the top of the boundary layer or fog will lift to form a stratus cloud layer.

An example showing this effect is presented in Figure 5 where the atmospheric stratification is initialized with two different inversion strengths. For the fog case, the boundary layer top is capped by

a potential temperature increase of about 8 °C, whereas the stratus case has a temperature increase of about 3 °C. Radiative cooling in both cases forces a decrease in the boundary layer temperature, however, after a short delay, the stratus case boundary layer depth increases more rapidly in comparison with the fog case. Stronger entrainment of dry air prevents the stratus case from reaching saturation near the ground, limiting the overall thickness of the cloud.



**Figure 5.** *Cloud mixing ratio (shaded, kg/kg) and potential temperature (contour) for (a) fog case and (b) stratus case. Increased entrainment in the stratus case prevents cloud from extending to the surface.*

## RELATED PROJECTS

Coupling techniques developed as part of this research are currently being used as part of the NOPP Community Sediment Transport Model development.

## PUBLICATIONS

Perlin, N., E. D. Skyllingstad, and R. M. Samelson, 2010: Coastal atmospheric circulation around an idealized cape during wind-driven upwelling studied from a coupled ocean-atmosphere model, *Mon. Wea. Rev.*, Accepted.